Chapter 4. Development of a Launch Vehicle Manufacturing Process

Introduction:

One of the goals of this chapter is to provide sufficient information so that you can develop a manufacturing process for a potential launch vehicle. With the variety of manufacturing options available, you might ask how this can possibly be done in the span of a single chapter. Actually, it will be quite simple because a basic manufacturing process is nothing more than a set of logical steps that are iterated until they produce a desired product. Although these statements seem simple and logical, don't let this simplicity fool you. Manufacturing problems with launch vehicles and their subassemblies have been the primary cause of project failures because the vehicle concept delivered to the manufacturing floor could not be built as designed.

In pursuit of our goal, let's begin by identifying the steps involved with a basic manufacturing process: design, material selection, manufacturing process selection, the manufacturing process implementation, and documentation of the process and its results (Table 4.1). As depicted in Figure 4.1, the steps are not intended to be stand-alone input/output operations; rather, they are parts of an overall iterative process. When a particular step produces an undesirable result, the process should be iterated back to the previous step and revised until a more suitable result is achieved. Also note the numerous "subelements" that feed into each step. This chapter will discuss these subelements in detail to provide you with sufficient information to make a decision on how to manufacture a launch vehicle.

Table 4.1. Steps in the Manufacturing Process

Step Number	Step	Description/Parameters	References
1	Design	Mission Requirements and Constraints Concurrent Engineering Building Block Approach Design for Manufacturing Computer-Aided Engineering Rapid Prototyping	
2	Material Selection	Metals Nonmetals	
3	Manufacturing Process Selection	Metal Processing Nonmetal Processing	
4	Manufacturing Process Implementation	Schedule/Cost Subcontractor Selection Control Inspection Quality Sustaining Engineering	
5	Documentation	Material Specifications and Standards Process Specifications Detailed Process Instructions	

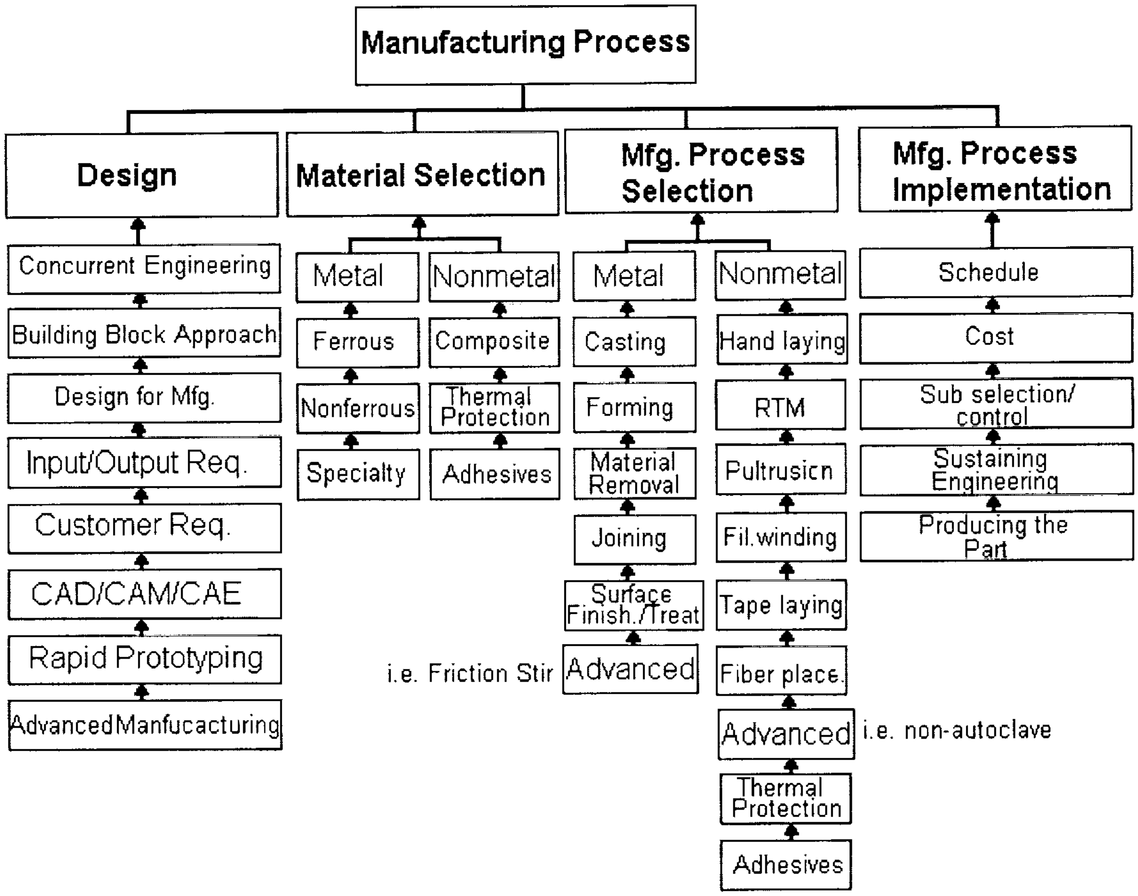

Figure 4.1. Manufacturing Process (being updated)

Like the other chapters in this book, we will to use the example ELV project to help you understand how to apply the techniques, and we will discuss other issues that must be considered if the potential launch vehicle is reusable.

STEP 1. DESIGN

The designer who wants to intelligently chaperone a launch vehicle from the requirements document to operational capability, while retaining control over budget and schedule, will be guided by concurrent engineering principles, will apply a building-block approach to the project, and will incorporate design for manufacture (DFM) principles throughout the process. Commitment to these three effective and complementary tools is guaranteed to reduce project risk - especially in the manufacturing and assembly phases -- and to increase the probability that the desired product will be delivered on time and within budget and will be operational.

Concurrent Engineering

The successful designer understands the industry maxim that 70 to 80% of the project development cost is determined by decisions made during the design phase. To avoid potential pitfalls during this key phase of product development, concurrent engineering principles should be utilized, which emphasize the use of multidisciplinary teams to design and manufacture a product.

The designer can sidestep the many risks associated with manufacturing by involving materials, processes, producibility, manufacturing, and inspection experts from the outset of the project. These are the people who command knowledge about materials and processes that will enhance the project, who understand the capabilities of today's manufacturing technologies, and who make it their business to integrate materials, processes, components, equipment, and workforce talent. When materials, manufacturing, and producibility expertise is tapped from the outset of a project, a parallel development effort begins that can avoid, neutralize, or counterbalance major schedule and cost obstacles. Early involvement can and will eliminate problems in the fabrication phase, assuring selection of the optimum processing methods and sequences of fabrication. On the other hand, a serial approach from design to manufacture almost always guarantees budget overruns and delays.

The benefits of practicing an integrated concurrent approach to project development can be readily calculated in terms of time and dollars saved. Similarly, the price of not employing a concurrent engineering philosophy is also easily calculated from the schedule delays and cost overruns common to programs governed by a serial development approach.

Table 4.2 lists the materials, processes, manufacturing, and producibility disciplines that should be represented for the concurrent engineering team for the designer to have authoritative insight into the manufacturing process.

Table 4.2. Typical Concurrent Engineering Expertise for Successful Manufacturing

PROJECT TEAM EXPERTISE	CONTRIBUTIONS
Manufacturing	-Tooling requirements -Process specifications -Effects of process interaction or conflict -Producibility determination
Materials	-Feasibility studies -Properties and performance -Allowables determination -Failure scenarios
Safety	-Safety guidelines -Risk management/mitigation procedures
Quality Inspection	-Inspection procedures -Quality control guidelines
Cost/Accounting	-Project costs

Building-Block Approach

Complementing the practice of concurrent engineering is the building-block approach. In a recent assessment of the state-of-the-art in the design and manufacture of large composite structures, NASA's Center of Excellence for Structures and Materials reported that "successful programs have used the building-block approach with a realistic schedule that allows for a systematic development effort."[1]

The building-block approach is a systematic, structured, rigorous method for achieving a desired end product, developing new technology, and resolving technical challenges. It offers the highest probability of success because it "builds" a complete system from literature research, test, and development to full-scaled demonstration and production. Each developmental step receives input from previous events and successes and uses decision gates to track progress and guide action plans, until the ultimate objective is achieved. Figure 4.2 illustrates this process as used by NASA's Marshall Space Flight Center.

Design for Manufacturing

The Design for Manufacturing (DFM) approach considers design decisions that affect fabrication, assembly, inspection, and test operations. Beginning in the conceptual design phase of project development, the process focuses on the capabilities of the materials and processes being considered for use and their associated potential problems -- the goal being to optimize the manufacturing methods while considering quality, reliability, cost, and schedule. Through analysis of design documentation, the team can determine if the design is technically and economically feasible to produce.

Early involvement of the manufacturing discipline is necessary to define the inputs, outputs, and trade studies required for both technology development and production tasks. Table 4.3 lists the inputs that must feed into the DFM process, the outputs the manufacturing team will provide the CE team, and the necessary interactions among organizations. Table 4.4 describes the types of trade studies that may be needed.

[1] Harris, C. E., Starnes, J. H., Jr., and Shuart, M. J., "An Assessment of the State-of-the-Art in the Design and Manufacturing of Large Composite Structures for Aerospace Vehicles", NASA/TM-2001-210844, National Aeronautics and Space Administration, Hampton, VA, April 2001

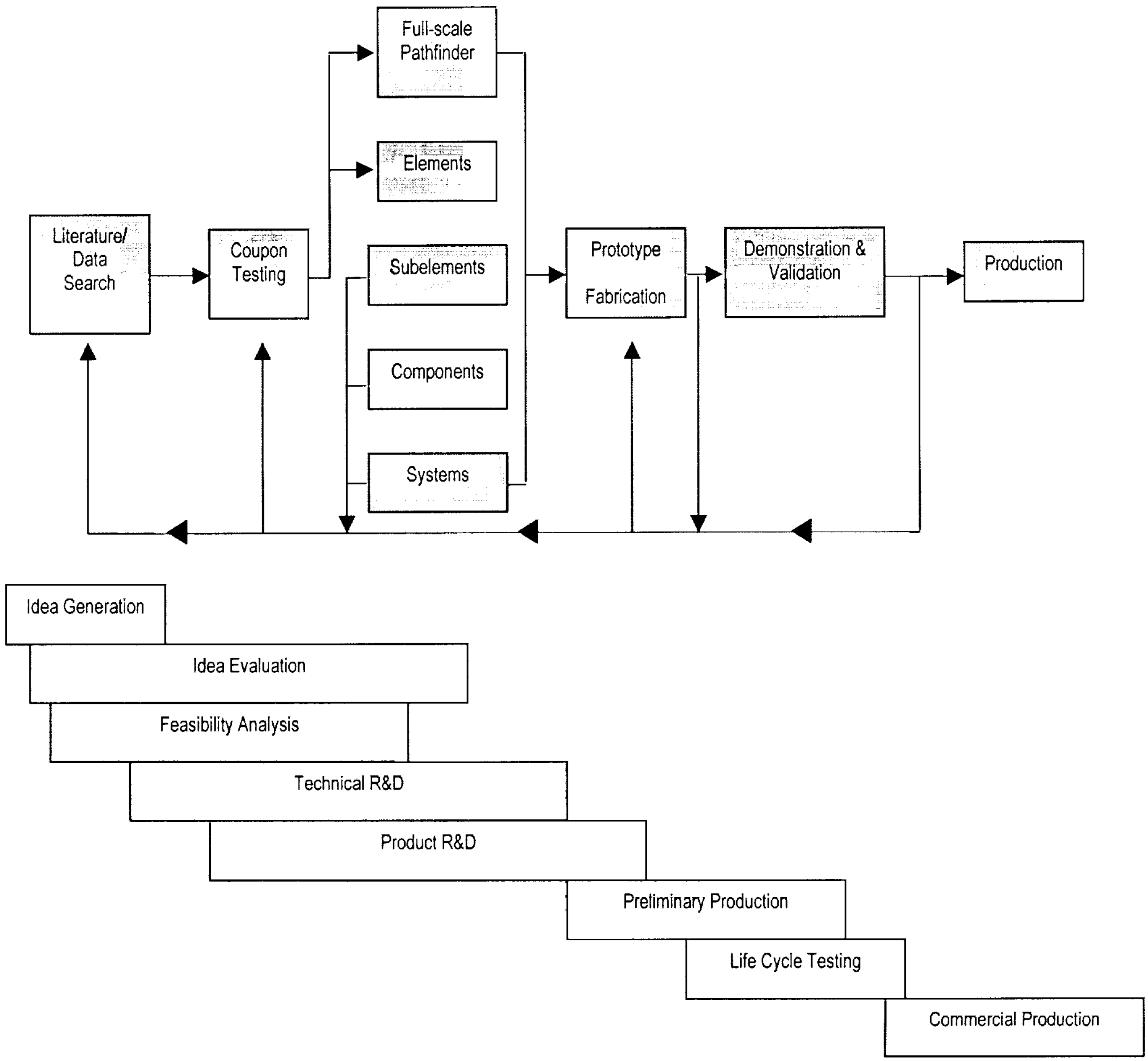

Figure 4.2. Building-Block Approach (reworking this)

Table 4.3. Inputs, Outputs, and Organizational Interactions

INPUT	OUTPUT	INTERACTIONS
Programmatic		
Production size Production schedule Application Expected life	End product Quality records Documentation Cost estimates Demonstration hardware Rapid prototyping model	
Technical		
Operating environments Special procedures Design parameters Drawings – part geometry Criticality of joints Interface requirements Material specifications Mechanical loads/properties Tooling requirements Special test designs Material compatibility Coating requirements Mechanical interfaces Critical inspection requirements	Material property data Material recommendation Test specimens NDE data Process sensitivities Process specifications Process recommendations Production schedule Delivery date	

Table 4.4. Typical Trade Studies Conducted During Product Development

TRADE STUDY	CONSIDERATIONS
Availability and Maturity of Technology	Performance requirements Reliability of technology Availability of material selected Level of material characterization Complexity of the design Availability of the process Risks
Facility Infrastructure	In-house vs. out-of-house capabilities Availability/capability of equipment Environmental requirements (temperature, humidity, particulate and molecular contamination) Pathfinder requirement
Workforce	Location of process expertise (In house? Out of house?) Experience base Completion of process characterization
Automation	Is automation an option?
Inspection	Is component or assembly inspectable?

Customer Requirements

As part of the concurrent engineering team, the designer will provide a desired vehicle design with production and acceptance requirements, and the customer will state performance requirements. Some of these requirements will dictate the manufacturing process to be used, but in this preliminary, iterative design sequence, suggestions should be fed back to the designer that may simplify production and maintain or even improve performance objectives.

Customer requirements may be "soft" or "hard." "Soft" requirements can be changed or modified, based on negotiation with manufacturing and on any technology leaps required. "Hard" requirements are those that must be met to achieve a successful launch, e.g., minimum altitude to gain date or a minimum payload capability. By the Preliminary Design Review stage, all requirements - both hard and soft - should be on the negotiating table. This allows the CE team to consider what requirements can be added or subtracted to meet both cost and schedule drivers.

Computer-Aided Engineering

Current technology provides many tools for the designer to verify success of the design before production ever begins. Computer-Aided Engineering (CAE) includes Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), prototyping, kinematics simulations/optimizations, and realistic animation. These powerful tools are used to model launch vehicle operational environments and to assess launch vehicle manufacturing processes for efficient engineering, design, analysis, simulation, optimization and component fabrication. All allow computer simulations of the parts, their production, and their performance individually and as integrated into the larger components. Rapid prototyping allows the designed parts to be quickly modeled out of a non-structural material. These three-dimensional parts can be assembled to check tolerances and other design features without the cost impact of actual production.

Based on CAE principles and guidelines, engineers and scientists interactively design, optimize, and verify manufacturing process through 3-D associative graphics, through which engineering changes can be handled easily and rapidly. These geometrically designed computer models can be used to produce drawing sheets, generate tool paths for machining applications, or fabricate rapid prototype models in a matter of hours. The CAD models can also be used to generate 3-D simulations to design and optimize processing/manufacturing workcells, especially when a multi-axial robot is involved. The Numerical Controlled machine codes or robotics codes generated can be transferred electronically to appropriate machines for processing. These capabilities are valuable for space hardware production, since most parts and components are one of a kind and are made of expensive materials. These factors severely limit the use of development prototypes for process optimization.

Advanced robotic off-line programming is made possible through sophisticated kinematics simulation 3-D graphical workcells, which make it possible to review the operational scenarios and design processes. Accurate simulations are made possible by incorporating actual robot attributes, including motion planning, kinematics, dynamics, and input/output (I/O) logic.

Rapid Prototyping/Rapid Manufacturing

Rapid Prototyping (RP) has become a crucial part of the design-to-manufacturing process; it is used from the early design verification stages to functional testing of a prototype. RP refers to a collection of additive manufacturing processes that fabricate wax, plastic, wood, or metal representations of a part design directly from the CAD model. RP techniques apply thin layers of material to "print" the selected parts from the bottom-up, allowing the creation of complex geometries in just minutes or hours. RP patterns are used for investment and sand casting forms; the more functional wood or plastic patterns are applied as fit-check verifications in assemblies as well as flow analysis test hardware. Metal RP patterns are progressing toward direct manufacturing of hardware.

Although technically a manufacturing process, Rapid Manufacturing (RM) is so closely related to RP that it deserves a brief mention. RM refers to the use of RP processes to fabricate end products. RM is used for short-run production and mass customization, in which every part is slightly different and, therefore, cannot be mass-produced by tooling and fixturing in the traditional methods. RM techniques include metal deposition processes, which fuse layers of metal or semi-metallic material to form the shape; ceramic processes that typically deposit or fuse a "green" state of the material, which requires binder burnout and sintering; and standard plastic deposition technologies.

Now that we have explored the various concepts that feed into the design side of a successful launch vehicle manufacturing process, let's look at the various manufacturing options that are available to us. First, we will examine the materials from which our parts can be made; then we will examine the various manufacturing techniques that are available to actually construct the launch vehicle components.

STEP 2. MATERIAL SELECTION

While the selection of materials for aerospace programs is heavily influenced by program maturity, i.e., whether the program is developmental or established, and the level of material characterization, the designer ultimately must select materials by considering both the operational requirements and the design engineering properties of the candidate materials.

Typical operational requirements include, but are not limited to, application, operational environment (transient or steady-state; static or dynamic loads; temperature; chemistry), contamination, life expectancy, and induced and natural space environments. Note that many of the natural environments experienced by launch vehicles are detrimental, e.g., temperature extremes, atomic oxygen, debris, radiation. These conditions should receive special consideration during the materials selection process. Once understood, operational requirements must be matched with the particular engineering properties of the candidate material. Some of these properties are detailed below:

- Mechanical (strength, toughness, ductility, hardness, thermal expansion, elasticity, fatigue, creep, specific strength and stiffness, fracture)
- Microstructural [atomic bonds, crystallinity (crystalline, amorphous, partly crystalline), polymer chains]
- Chemical (corrosion, general degradation of properties, toxicity, flammability;)
- Physical (density, specific heat, thermal expansion, thermal and electrical conductivity, melting point, electrical, magnetic,)
- Compatibility with manufacturing methods (heat treatment, tempering, surface treatment, joining, composites, laminations, fillers)
- Compatibility with other materials (reaction issues, coating requirements, vacuum outgassing)
- Compatibility with test/inspection processes

- Availability (lead-time to procure)
- Cost

For our purposes in this chapter, we will divide the available materials from which to choose into metals and nonmetals. Be aware that some applications are best served by metallic materials, others by nonmetallic materials. You must consider the application requirements as well as the material properties and capabilities during material selection.

Metals

Traditionally, metals are incorporated into a design because they possess good thermal and electrical conductivity, tensile strength, hardness, elasticity, malleability, ductility, and a general resistance to stress. These properties have made metals the material of choice to serve in various structural and electrical applications. Despite their beneficial properties, several trade-offs become apparent when dealing with metallic materials. Designers must be aware that metal selection is a balancing act between the ultimate strength of the metal versus other properties, including fatigue strength, fabricability, fracture toughness, inspectability, material cost, characterization cost, and weight. Indeed, the final point of strength versus weight is probably the most important when dealing with launch vehicle designs because of the inherent need for lightweight/high-strength materials.

Table 4.5 depicts the most common types of metals and a brief description and common examples of each.

Table 4.5. Categories of Metals and Their Properties

METAL	PROPERTIES	EXAMPLES
Ferrous (iron - based)	High strengths (ultimate, yield, fatigue), lower costs than nonferrous	Steels (carbon, alloy, stainless, tool/die) and cast irons
Nonferrous	Corrosion resistant, thermal electrical conductivity, low density, ease of fabrication	Aluminum, beryllium, copper, cobalt, lithium, magnesium, nickel, superalloys, titanium, refractory metals, precious metals
Specialty	Unique to type	Amorphous metals (metallic glass alloys), shape memory alloys

New and continuing developments in metals and metals processing are significantly expanding the designer's toolkit. For example, the development and use of aluminum-lithium alloys represent the state-of-the-art in metallic launch vehicle applications and how design requirements can drive material selection. This development came about after increased payload weights projected for construction of the International Space Station forced designers to search for ways to reduce the Shuttle's overall weight. They relied on advances in metallurgy and joining technology, eventually determining that the External Tank propellant tanks, originally constructed of 2219 aluminum, could be successfully replaced with an aluminum-lithium-based alloy that was 30% stronger and 5% less dense. The resulting Super Light Weight Tank (SLWT) provided a 7,500-lb reduction in overall weight, which directly contributed to the Shuttle's increased payload carrying capability. All of this was accomplished by changing the selected metal and some of its associated manufacturing techniques. Other emerging developments in the fields of metal-matrix composites are producing metallic materials with increased elastic modulus, better toughness properties, and higher temperature capabilities --all key benefits in any launch vehicle design.

Now, let's look at the wide range of nonmetals that are available.

Non-Metals

The aerospace industry relies on non-metallic materials primarily for structural, insulating, lubricating, electrical/electronic, and adhesive applications. The three general categories of non-metallic materials are composite materials (structural polymer matrix composites and ceramic matrix composites), thermal protection materials (cryoinsulations and ablative insulations), and adhesives.

A composite material is a macroscale combination of materials that attempts to provide increased capability by using the advantages of each constituent material. Most composites take the form of a reinforcing material (fibers, for example) imbedded or surrounded by a matrix material (resin). Carbon, glass, and aramid-type fibers are the most common reinforcement materials used in aerospace applications. These fibers provide the effective strength and rigidity of the overall part, while the matrix material protects the fiber from damage, helps keep proper fiber position, and provides the means to alter chemical and electrical properties. Thermoset or thermoplastic materials are usually used as matrix materials, depending on the required strength and expected temperature loads. Commonly used matrix materials include epoxy, phenolic, and ester-based resin systems. Composite materials, when compared to metals, provide a much greater strength-to-weight ratio, exhibit increased resistance to corrosion, and can be more easily tailored to meet the design requirements, *e.g.*, changing fiber or matrix.

Thermal protection materials, as implied by their name, are designed to protect and insulate other components from extreme thermal stresses associated with launch vehicle operations. Collectively, the thermal protection materials designed for launch vehicle applications are known as the Thermal Protection System (TPS). TPS systems use radiative, conductive, ablative, and convective forms of heating/cooling to ensure that components remain protected throughout the launch and operational thermal profile of the vehicle. Various forms of TPS materials may include, but are not limited to:

- insulative materials, which reduce airflow across a thermal gradient to reduce heat exchange capability
- radiative materials, which effectively radiate the heat away from a hot surface without any mass loss or shape change
- absorptive materials, which tend to change mass and shape as they absorb heat through ablation, heat sinking, or transpiration.

Two examples of thermal protection materials show the extraordinary capabilities offered by a vehicle's TPS system. The Space Shuttle felt- and tile-based TPS maintains the Orbiter's primary aluminum structure at a temperature less than 350 °F, while externally the Shuttle may experience temperatures that range from –250 °F up to almost 3000 °F[2]. On the other hand, cryoinsulation-type foams are applied to launch vehicle propellant tanks to reduce "boil-off" of propellants, which typically must be maintained at approximately –450 °F to operate efficiently.

[2] Jenkins, 395 (add details)

Adhesives are defined as materials that have the capability to hold other materials together by surface attachment. Many types of adhesives are available to perform bonding operations, which may range from simple "super glue" type adhesives used to bond strain gauges onto components to complex multi-part mixable adhesives used to bond rocket nozzle metallic and composite materials together in high-heat environments. The primary types of adhesives include epoxies, acrylics, cyanoacrylates, anaerobic systems, silicones, and urethanes. These provide vastly different performances that can be tailored to suit the specific environmental conditions expected near the bonding location. In addition to their independent properties and capabilities, some of these systems can be combined to create optimized bonding systems that have all of the advantages of the individual adhesives.

With such a wide array of uses for nonmetallic materials, the number of challenges facing some applications is not surprising. All applications relying on nonmetals can be affected by a volatile raw material market; obsolescence issues, strict environmental guidelines, and low-quantity production -- which often means a low profit product for many companies - can affect material availability and cost. Rarely can companies afford to expend vast amounts of research and development money to develop a nonmetallic that is likely to be used only on a few launch vehicles. Table 4.6 lists some disadvantages for each category of nonmetallic material.

NONMETAL	LIMITATIONS
Composites	☐ Damage tolerance and fatigue data must be generated on a case-by-case basis because of lack of sufficient modeling capability ☐ Repair of large structures is difficult. ☐ Difficulties exist in applications where metallic and composite joining is required, e.g., bonding, fasteners ☐ Most composites rely on expensive machines for fabrication ☐ Difficulties exist in joining large sections of composites to one another
Thermal Protection Materials	☐ Variations in processing parameters (spray temperature and humidity, relationship of material to unique processing) result in vastly different insulating capabilities ☐ Consistency of end-product has high degree of variability in insulation, even with same quality of material and process ☐ A low reusability capability in general ☐ Higher material costs associated with R&D and complex manufacturing processes ☐ Need for hand-sprayable processes for repair and closeout (ablatives) ☐ Need for self-diagnostic, reusable forms of ablative insulation
Adhesives	☐ Development of higher performance materials that are "process friendly," *i.e.*, have higher temperature capabilities (>350 °F), improved toughness, and higher strength ☐ Development of materials that cure at room temperature or at simple elevated temperatures (>180 °F); store at room temperature, have long shelf lives and out times; have good tack

Table 4.6. Categories of Non-Metals and Their Limitations

With a basic knowledge of nonmetallic materials and some of their advantages and limitations, let's look at Tables 4.7 through 4.12, which present the materials and important properties of each.

Table 4.7. Fiber-Reinforced Ablative Materials

Constituent	Important Properties
Fiber Reinforcement	
Carbon	
Rayon-based	Low thermal conductivity, strength/stiffness; good interlaminar properties
Polyacrylonitrile (PAN)-based	Higher thermal conductivity, tailorable strength, stiffness; low interlaminar strength
Silica	Used in low temperature applications; compatible with oxidizing environments
Matrix	
Phenolic*	Tough, stable char; high char yield resin, relative inexpensive
Other resins	Used for hot, non-reusable applications
Fillers	
Carbon black	Used for carbon phenolics
Carbon, glass microballoons	Used to create low-density ablatives

* Predominant matrix used in ablative applications

Table 4.8. Fiber-Reinforced Structural Polymer Matrix Composites

Constituent	Important Properties
Fiber Reinforcement	
Carbon	
PAN-based	High modulus, high strength
Pitch-based	Ultra-high modulus, high strength, excellent dimensional stability
UHM PAN*	Ultra-high modulus, 2x strain capacity of pitch, excellent dimensional stability
Glass	Heavier than carbon, inexpensive

Aramid	Light-weight, high performance, poor compression properties
Matrix	
Epoxy	Longest used structural resin, improved damage resistance
Cyanate Ester	Very hydrophobic, best dimensional stability with Pitch- or UHM PAN fibers
Phenolic	Higher temperature, used more with ablatives, structural application in ET CNC**
Bismaleimide	Higher temperature, processes similar to epoxy
Polyimide	High temperature polymer resin, very difficult to process
Thermoplastic	Melt (vs. cure/set); repairs possible with localized heating; adapted for automated processing

* Ultra-High Modulus PAN
**External Tank Composite Nose Cone

Table 4.9. Fiber-Reinforced Ceramic Matrix Composites

Constituent	Important Properties
Fiber	
Continuous (carbon, silicon carbide, aluminum oxide) Extruded monolithic (hafnium carbide, silicon carbide)	Provides strength
Fiber Interface	
Carbon, boron nitride Tungsten-rhenium-hafnium carbide	Enables toughness for continuous fiber CMCs
Matrix	
Silicon carbide Silicon nitride Aluminum oxide Zirconia carbide Hafnium carbide/silicon carbide Carbon	Binds fiber plies together; prevents interface coating and fiber environmental degradation
Coatings	
Sealing	Coats machined ends; gives additional environmental degradation protection
Environmental	Provides environmental protection

Table 4.10. Cryoinsulations

Constituent	Important Properties
Polyurethanes	
PDL-1034 SS-1171	
Polyisocyanoates	
NCFI 24-124 NCFI 24-57	

Table 4.11. Ablative Insulations

Constituent	Important Properties
Ceramic	
Adhesive	
Cork-Filled Epoxy	

Table 4.12. Adhesives

Constituent	Important Properties
Thermosets	

Epoxy	Good solvent resistance; good elevated temperature properties up to 300-350 °F; limited pot life; 2-part formulations require mixing; exothermic reactions; properties deteriorate in wet/hot environments
Polyurethane	Low temperature flexibility and toughness; complex mixing/application; moisture sensitive; poor elevated temperature performance; short pot life
Modified Acrylic	Good flexibility, peel, and strength wear; no mixing required (usually); minimal surface preparation required; poor elevated temperature performance; slow cure times; limited pot life; off gas flammable species
Cyanoacrylate	Good strength and ease of use; fast setting; good adhesion to metal substrate; high cost, poor durability on some surfaces; limited solvent and elevated temperature resistance
Thermoplastics	
Polyimides (TPI)	Extremely high service temperatures (>650-700 °F); high strength; poor processing characteristics, low tack, elevated temperature cure requirements (570-650 °F)

Once you have decided on the particular material that fulfills your design requirements, it is time to continue developing your manufacturing process by selecting the appropriate manufacturing method that you will use to transform the chosen raw material into a finished launch vehicle component.

STEP 3. MANUFACTURING PROCESSES SELECTION

The design of any manufactured component requires an adequate understanding of not only the selected material, but also of the various processing contributions that affect the final product. To that end, this section will detail the various manufacturing processes that are available for metals and nonmetals; this information will allow you to choose the process that best fits your application.

Manufacturing processes are dictated by standards to ensure consistency in production. These standards can be industry standards such as ASTM or AWS standards or they can be government standards such as DoD- or NASA-owned standards. These standards specify parameters in a manufacturing process or in quality inspection acceptance criteria.

Metal Processing

In our discussion of potential manufacturing processes, we will first examine the processes used to manufacture metallic components. Selecting the appropriate process will be based primarily on the properties of the chosen metal material. Certain metals are only compatible with certain manufacturing processes because of inherent material properties. These properties may range from the metal's machinability rating, which specifies how easy or how difficult the metal can be machined (see Material Removal section) to its behavior under high-temperature loads that may be experienced during casting or joining operations. You should carefully determine and fully understand the properties of the proposed metal before proceeding with a manufacturing process selection. In this section, we will describe in detail five metal manufacturing processes that are used in launch vehicle manufacturing today: material removal, casting, forming, joining, and surface finishing/treatment. Additionally we will briefly discuss several advanced techniques that recently have shown great promise in the field of metal manufacturing.

Material Removal

Material removal is a broad term used to describe metal processing techniques that involve the removal of metal to achieve a desired net shape or surface finish or to meet tolerances. Material removal processes are based on the same principles of metal chip formation, but they differ in how the cutting tools interact with the work piece and in the type of cutting tools used. In this section, we will examine two potential material removal processes that are commonly used in launch vehicle manufacturing processes: turning and milling.

Turning is an operation in which a circular shaped work piece is rotated and a cutting tool is brought into contact with the rotating part to cut away material. The desired part must be symmetrical to use this method. This process is exemplified by lathe type operations where specific types of cutting tools or bits are traversed along the length of a rotating part. The cutting tool essentially shaves off a certain depth of material each time it makes a pass along the part, making this process ideal for reducing the diameter of rod or tube shaped parts. A variation on the turning method, commonly called the cut-off method, places the cutting tool perpendicular to the rotating part and allows it to travel radially toward the part's center. This process can be used to completely cut through the part or can be stopped at required depths like those required for o-ring grooves.

While turning processes rely on a rotating part interacting with a semi-stationary cutting tool, milling techniques rely on a rotating cutting tool interacting with a stationary part. This allows for material removal of shapes that aren't circular in nature. Milling processes are generally divided into two main categories: slab milling and end milling. The primary difference between the two is that, in slab milling, the cutting tool is parallel to the material surface; in end milling, the cutting tool is perpendicular to the material surface. In both cases, specialized milling machines use a rotating bit that travels along the material to cut away unnecessary metal, essentially shaving off small layers of metal until the desired dimension is obtained.

Although the material removal processes described above may seem simple at first glance, the affects of many parameters must also be fully understood before proceeding with the chosen operation. Some of these parameters include part feed or rotational speed, depth of cut, tool angles, expected temperatures (coolant requirement), and expected tool wear rates.

Let's look now at some non-traditional methods of metal removal.

Chemical and Electro-Chemical Machining

While these processes sound and appear similar, their fundamental principles are quite different. <u>Chemical machining</u>, also called chemical milling, produces the desired shape by dissolving the metal with chemical solution. Metal removal begins as the solution contacts the metal. Masking is used to control part geometry, isolating the sections not to be machined. The solution will remove metal as long as it contacts the metal, until the metal has completely dissolved, or until the solution is saturated with metal solute.

Electro-chemical machining removes metal by liberating ions from the work piece in a sustained current flow from the work piece (anode) to a tool (cathode). An electrically conductive solution (electrolyte) provides the conductive medium and is usually kept flowing to carry away the metal ion. The solution, by itself, does not remove any metal. Machining only occurs when the current is flowing. Metal is removed in direct proportion to current density, which is affected by part and tool geometry. Baffles are also used to manipulate current densities.

Both processes can produce complex shapes in less machinable metals or parts that are difficult to fixture or access with conventional machining. To benefit fully from the precision these processes offer, the material must be homogeneous at the microstructural level. Since different metals will be removed at different rates, metals with alloy-rich regions or assemblies comprising different materials are not good candidates for either of these processes. While the rate of metal removal is slow (low?), large areas of a part can be machined; so overall part production is competitive with conventional machining, particularly for large parts. These processes also eliminate the need for deburring and chip removal associated with conventional cutting.

Electrical-Discharge Machining (EDM)

Electrical-discharge machining (EDM) uses rapid electrical arcing from an electrode to the work piece to remove metal. Arcing occurs through a dielectric fluid, which carries away the metal debris and cools the part. Electrode shapes influence the shape of the cut on the work piece and fall into two types. Stick shapes are used to plunge and translate into a part and to machine deep features or complex cavities. Wire electrodes consist of a continuous loop or line of wire that is slowly pulled through the part as it cuts. This configuration is similar to a band saw, where the wire enters the part at a free edge. Both the wire and part can be manipulated in multiple axes under computer control to cut complex shapes and intricate patterns in materials that are difficult to cut conventionally.

Laser Beam Machining

Laser beam machining directs a high-energy laser beam, either continuous or pulsed, to melt material on the work piece. Air or inert gas can be used to assist in removing the molten metal. Precise computer control and a narrowly focused beam (< 1 micron) (check this figure) enable the process to machine intricate details to high tolerances. Machining and cutting performance depend on laser power and the reflectivity and melting point of the work piece material. As with EDM, laser beam machining is useful for parts that are difficult or impractical to machine by conventional methods. Surface finish and heat effects are important considerations for laser beam machining. The surface effect of a laser on a work piece can also be used to etch parts for identification or other marking, often in ways that are impossible to detect with the unaided eye.

Water Jet Machining

Water jet machining uses a high-pressure (60 to200 ksi) stream of water to cut material, with or without the addition of abrasive particles. Similar to laser beam machining, cuts can be started anywhere on the work piece, with little or no mechanical force applied to the part. It can be used to cut both very thin and very thick materials where traditional machining is often less effective. Abrasive particles can be added to assist in cutting thick sections, hard metals, and difficult composites.

Despite the obvious benefits that material removal techniques provide, there are some associated disadvantages. Material removal machines used for launch vehicle manufacturing applications require the use of a precise locating and indexing system to ensure that proper tolerances and dimensions are maintained. Many of these machines use some form of a computer numerical control system, which is a dedicated computer that controls the movement of the machine based on a set of programmable instructions. This system, along with the requirement for precision moving mechanisms, tends to increase the costs required to obtain material removal equipment. Regardless of the capability of the chosen equipment, there will be some very complex shaped parts that may not be compatible with either turning or milling techniques due to interference with the tooling setup. Taking a tip from the design for manufacture concepts discussed earlier, designers must fully understand the capabilities of the equipment and incorporate this knowledge into their part design.

Casting
Metal casting is a process in which molten metal is delivered into a shaped mold, is allowed to solidify, and then is removed. Typically, metals are cast in one of two ways: using either expendable or permanent molds. As the names imply, expendable mold casting (also called investment mold casting) discards the mold, and permanent mold casting reuses mold tooling after each part is produced. The advantages and disadvantages of some typical casting processes are described in Table 4.13.

Table 4.13. Typical Metal Casting Processes

PROCESS	DESCRIPTION	ADVANTAGES	DISADVANTAGES
Sand	Casting sand is used to make a mold of the part to be cast.	Can cast most metals; no size, weight, shape limit; low cost tooling	Post cast machining required, wide tolerances
Investment	A wax pattern is coated with refractory material; the wax is melted out, and the remaining "shell" is filled with molten metal	Can cast most metals; can produce intricate shapes; excellent surface finish	High-cost patterns, molds, labor; limited part size
Die	Molten metal is forced by pressure into a permanent mold or die.	High production rate; excellent tolerances and surface finish	High-cost dies; limited part size; usually limited to nonferrous metals
Centrifugal	Inertial forces spin molten metal against a mold wall.	High production rate; can produce large cylindrical shapes	High-cost equipment, limited part geometry

Forming
Forming is the general term applied to metal manufacturing processes that use various dies and tools to shape metal. Table 4.14 presents a small subset of forming processes that may be useful in manufacturing a launch vehicle.

Table 4.14. Forming Processes

PROCESS	DESCRIPTION	TYPICAL PRODUCTS
Rolling	Continuous work piece passes through compressive rollers to reduce cross-sectional area	Structural shapes, fuselage panels
Forging	Compressive forces are applied to the work piece by various dies and tooling	Bolts, rivets, shafts, gears, etc.
Extrusion	Metal material is forced through a shaped die	Structural profiles
Powder Metallurgy	Metallic powders are compacted to produce shaped components	Landing gear struts, nacelle frames, turbine blades
Stamping	Parts are punched, bent, or stamped from thin metallic sheets	Complex thin-walled profiles and shapes

Joining
Metallic parts can be joined using a wide range of methods -- from mechanical fasteners to very complex welding procedures.

Joining with mechanical fasteners uses various types of fasteners such as bolts, nuts, screws, staking, swaging pins, clips, and rivets. Fastener selection must take into account a number of variables, including the type of screw thread required for the given application, the appropriate head size required to distribute loading, the edge distance required to reduce pullout (generally 1.5 times the depth of the fastener), the material